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Independent Effects of Age, Education, Verbal Working Memory, Motor Speed of Processing, Locality, and Morphosyntactic Category on Verb-Related Morphosyntactic Production: Evidence From Healthy Aging

Marielena Soilemezidi,[a,b] Maki Kubota,[c] Marina Chrisikopoulou,[b] Valantis Fyndanis[b,d]

[a]*Department of Linguistics (Faculty of Philology), National and Kapodistrian University of Athens*
[b]*Department of Linguistics and Scandinavian Studies, University of Oslo*
[c]*Department of Language and Culture, University of Tromsø – The Arctic University of Norway*
[d]*Department of Rehabilitation Sciences and Disorders, Cyprus University of Technology*

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Abstract

This study investigates the role of locality (a task/material-related variable), demographic factors (age, education, and sex), cognitive capacities (verbal working memory [WM], verbal short-term memory [STM], speed of processing [SOP], and inhibition), and morphosyntactic category (time reference and grammatical aspect) in verb-related morphosyntactic production (VRMP). A sentence completion task tapping production of time reference and grammatical aspect in local and nonlocal configurations, and cognitive tasks measuring verbal WM capacity, verbal STM capacity, motor SOP, perceptual SOP, and inhibition were administered to 200 neurotypical Greek-speaking participants, aged between 19 and 80 years. We fitted generalized linear mixed-effects models and performed path

Correspondence should be sent to Valantis Fyndanis, 95 Irinis, CII Building, 2nd Floor, Room 217, 3041 Limassol, Cyprus. E-mail: c.fyndanis@cut.ac.cy

analyses. Significant main effects of locality, age, education, verbal WM capacity, motor SOP, and morphosyntactic category emerged. Production of time reference and aspect did not interact with any of the significant factors (i.e., age, education, verbal WM capacity, motor SOP, and locality), and locality did not interact with any memory system. Path analyses revealed that the relationships between age and VRMP, and between education and VRMP were partly mediated by verbal WM; and the relationship between verbal WM and VRMP was partly mediated by perceptual SOP. Results suggest that subject-, task/material- and morphosyntactic category-specific factors determine accuracy performance on VRMP; and the effects of age, education, and verbal WM on VRMP are partly indirect. The fact that there was a significant main effect of verbal WM but not of verbal STM on accuracy performance in the VRMP task suggests that it is predominantly the processing component (and not the storage component) of verbal WM that supports VRMP. Lastly, we interpret the results as suggesting that VRMP is also supported by a procedural memory system whose efficiency might be reflected in years of formal education.

Keywords: Healthy aging; Morphosyntactic production; Time reference/tense; Grammatical aspect; Age; Education; Sex; Short-term memory; Working memory; Inhibition; Speed of processing; Locality

1. Introduction

Although there are larger effects of aging on language production than on language comprehension (James & Goring, 2018), little is known about the role of aging in verb-related morphosyntactic production (VRMP); that is, in production of morphosyntactic categories associated with the verb such as time reference/tense and grammatical aspect. Furthermore, only a few studies have addressed whether VRMP is affected by cognitive capacities that decline with age, such as short-term memory (STM), working memory (WM), speed of processing (SOP), and inhibition (e.g., Calabria, 2023; Pliatsikas et al., 2019; Salthouse, 1996). Moreover, most studies report a female advantage in language production (e.g., Ardila & Rosselli, 1996; Angelopoulou et al., 2020; Moscoso del Prado Martín, 2017; Weiss, Kemmler, Deisenhammer, Fleischhacker, & Delazer, 2003). For instance, there is evidence that sex interacts with age regarding the amount of spontaneous speech (Ardila & Rosselli, 1996) and the diversity of syntactic structures produced in natural conversations (Moscoso del Prado Martín, 2017), with aging affecting male more than female neurotypical adults. However, it is still unknown whether the female advantage extends to VRMP. Likewise, the role of educational level and locality—a task/material-related variable (see Section 1.1)—in VRMP has not received much attention thus far.

The current study investigates the role of subject-specific variables (i.e., variables related to demographic factors and cognitive capacities) and task/material-specific variables (i.e., morphosyntactic categories under investigation and locality; see Section 1.1) in VRMP. Before presenting the research questions and corresponding predictions, we will provide background information on the task/material-specific variables of interest and the cognitive capacities considered. Next, we will briefly review evidence concerning subject- and task/material-specific variables in language production, with a particular emphasis on VRMP.

1.1. Background information on morphosyntactic categories of interest, locality, and cognitive capacities

1.1.1. Morphosyntactic categories of interest

Both *tense* and *grammatical aspect* are associated with the verb as these morphosyntactic categories are instantiated in verb morphology. *Tense* is used to locate events in time. For example, past tense locates an event prior to the speaking time, and future tense locates an event subsequently to the speaking time (e.g., Comrie, 1985). Tense is closely related to *time reference*, which is a semantic category. The close relation between the two lies in the fact that, in many languages, reference to different time frames (past, present, future) is made through tense. Nevertheless, since different tenses can refer to the same time frame (e.g., in English and in other languages, both simple past tense and present perfect refer to the past), and since the same tense can refer to two time frames (e.g., in Italian, present tense can refer to the present or to the future), tense is not identical to time reference. The present study focuses on time reference rather than tense. However, we will use these two terms interchangeably here.

Grammatical aspect refers to the way the speaker views an event (e.g., Comrie, 1976; Smith, 1997). The most fundamental aspectual distinction is that between *perfectivity* and *imperfectivity* (op. cit.). A speaker uses the perfective aspect when they view an event as a whole, without focusing on the various separate phases making up that event. When the speaker focuses on the internal structure of an event, they use the imperfective aspect. For example, the difference in the way the singing event is seen in sentences (1) and (2) reflects the aspectual distinction between imperfectivity and perfectivity, respectively.

(1) Yesterday I was singing the song "New York, New York" when Mary called.
(2) Yesterday I sang the song "New York, New York."

There is robust cross-linguistic evidence that time reference/tense is impaired in adult neurogenic language disorders such as stroke-induced agrammatic aphasia (e.g., Friedmann & Grodzinsky, 1997, for Hebrew; Gavarrò & Martínez-Ferreiro, 2007, for Catalan, Galician, and Spanish; Kok, van Doorn, & Kolk, 2007, for Dutch; Wenzlaff & Clahsen, 2004, for German; Nanousi, Masterson, Druks, & Atkinson, 2006, for Greek). In aphasia research, grammatical aspect has received less attention than time reference. However, several studies on Greek aphasia have focused on these categories, and found that they are both impaired (Fyndanis, Varlokosta, & Tsapkini, 2012; Fyndanis, Arcara, Christidou, & Caplan, 2018; Nanousi et al., 2006; Varlokosta et al., 2006; but see Protopapas, Cheimariou, Economou, Kakavoulia, & Varlokosta, 2016). It was also shown that grammatical aspect and/or time reference can be challenging for individuals with dementia of the Alzheimer type (DAT) (e.g., Fyndanis, Manouilidou, Koufou, Karampekios, & Tsapakis, 2013; Fyndanis, Arfani et al., 2018; Manouilidou, Roumpea, Nousia, Stavrakaki, & Nasios, 2020), for individuals with multiple sclerosis (Fyndanis et al., 2020; Grigoriadis et al., 2024) and for neurotypical middle-aged and older adults (e.g., Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022). Fyndanis and colleagues also found that grammatical aspect is more demanding than time reference, with this dissociation emerging in neurotypical adults (Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022), individuals with agrammatic aphasia (Fyndanis et al., 2012; Fyndanis, Arcara et al., 2018), individuals with DAT (Fyndanis et al., 2013), and individuals with multiple sclerosis (Fyndanis et al., 2020).

1.1.2. Locality

Locality is a task/material-related variable, which refers to whether the critical cue is adjacent to the target or not. For example, in item (3), which tests production of past reference, the critical cue is the time adverbial *yesterday* and the target the participant is expected to produce is the verb form *walked*. Since the subject *Mary* intervenes between the critical cue and the target, time reference is tested within a nonlocal configuration in (3). In the same vein, item (4) tests the production of subject-verb agreement within a local configuration because the critical cue (*Mary*) is adjacent to the target (*walks*). (For examples from Greek, see Table 1.)

(3) Tomorrow Mary will walk to work. > **Yesterday** Mary ***walked*** to work.
(4) Everyday I walk to work. > Everyday **Mary** *walks* to work.

1.1.3. Cognitive capacities of interest

In this study, we adopt the view that WM is the memory system that is responsible for storing and processing a small amount of information for a short period of time (e.g., Baddeley, 1986; Cowan, 2008). STM is the storage component of WM (e.g., Baddeley & Hitch, 1974; Baddeley, 1992). Moreover, we adopt the view that there are separate components for storing and maintaining verbal versus nonverbal material (e.g., Baddeley & Hitch, 1974; Baddeley, 1992).

A cognitive capacity closely related to WM is SOP (e.g., Salthouse, 1992; Fry & Hale, 1996, 2000). This construct represents "how quickly many different types of processing operations can be carried out" (Salthouse, 1996, p. 425). There is evidence that individual differences in WM capacity largely reflect individual differences in SOP (e.g., Salthouse, 1992). The main distinction that applies to SOP is that between *motor SOP* and *perceptual SOP*. It has been found that the relationship between age and accuracy performance on cognitive tasks tapping memory, reasoning, and spatial ability is partly mediated by perceptual SOP (Salthouse, 1994, 1996).

Moreover, we assume that there might be a procedural memory system that supports processing during language production and comprehension. Such a system could be long-term working memory (LTWM) for language (Caplan & Waters, 2013). The term LTWM was coined by Ericsson and Kintsch (1995), who proposed that LTWM is a WM system that is based on storage in long-term memory and is connected to skilled activities. Caplan and Waters (2013) argued that language constitutes a skilled activity, and—based on previous findings (e.g., Caplan & Waters, 1999)—proposed that on-line syntactic processing in comprehension is predominantly supported by LTWM for language, not by WM. Following Fyndanis et al. (2022), we assume that LTWM for language might also be involved in VRMP (see "Education effects" subsection in Section 1.2.2).

Inhibition, one of the most studied components of executive functioning, is "one's ability to deliberately inhibit dominant, automatic, or prepotent responses when necessary" (Miyake

Table 1
Examples of items tapping production of time reference and grammatical aspect (sentence completion task)

		TIME REFERENCE: **FUTURE**		
		LOCALITY	Source sentence	Target sentence
ASPECT	**Imperfective Aspect**	Local time reference/ Nonlocal aspect	*Mésa se misí óra aftós xθés mírase ta ðóra.* Within half an hour he yesterday distributed-PERF. the gifts (lit.)	*Epí misí óra aftós ávrio* ____________________. *(target: θa mirázi ta ðóra)* For half an hour he tomorrow ___________. (target: will distribute-IMPERF. the gifts) (lit.)
		Local aspect/ Nonlocal time reference	*Xθés aftós mésa se misí óra mírase ta ðóra.* Yesterday he within half an hour distributed-PERF. the gifts (lit.)	*Ávrio aftós epí misí óra* ____________________. *(target: θa mirázi ta ðóra)* Tomorrow he for half an hour ___________. (target: will distribute-IMPERF. the gifts) (lit.)
	Perfective Aspect	Local time reference/ Nonlocal aspect	*Epí misí óra* aftós xθés míraze ta ðóra. For half an hour he yesterday distributed-IMPERF. the gifts (lit.)	*Mésa se misí óra aftós ávrio* ____________________. *(target: θa mirási ta ðóra)* Within half an hour he tomorrow ___________. (target: will distribute-PERF. the gifts) (lit.)
		Local aspect/ Nonlocal time reference	*Xθés aftós epí misí óra* míraze ta ðóra. Yesterday he for half an hour distributed-IMPERF. the gifts (lit.)	*Ávrio aftós mésa se misí óra* ____________________. *(target: θa mirási ta ðóra)* Tomorrow he within half an hour ___________. (target: will distribute-PERF. the gifts) (lit.)

(*Continued*)

Table 1
(Continued)

			TIME REFERENCE: **PAST**	
ASPECT	**Imperfective Aspect**	Local time reference/ Nonlocal aspect	*Mésa se misí óra aftós ávrio θa mirási ta ðóra.* Within half an hour he tomorrow will distribute-PERF. the gifts (lit.)	*Epí misí óra aftós xθés ____.* *(target: míraze ta ðóra)'* For half an hour he yesterday ____. (target: distributed-IMPERF. the gifts) (lit.)
		Local aspect/ Nonlocal time reference	*Ávrio aftós mésa se misí óra θa mirási ta ðóra.* Tomorrow he within half an hour will distribute-PERF. the gifts (lit.)	*Xθés aftós epí misí óra ____.* *(target: míraze ta ðóra)* Yesterday he for half an hour ____. (target: distributed-IMPERF. the gifts) (lit.)
	Perfective Aspect	Local time reference/ Nonlocal aspect	*Epí misí óra aftós ávrio θa mirázi ta ðóra.* For half an hour he tomorrow will distribute-IMPERF. the gifts (lit.)	*Mésa se misí óra aftós xθés ____.* *(target: mírase ta ðóra)* Within half an hour he yesterday ____. (target: distributed-PERF. the gifts) (lit.)
		Local aspect/ Nonlocal time reference	*Ávrio aftós epí misí óra θa mirázi ta ðóra.* Tomorrow he for half an hour will distribute-IMPERF. the gifts (lit.)	*Xθés aftós mésa se misí óra ____.* *(target: mírase ta ðóra)* Yesterday he within half an hour ____. (target: distributed-PERF. the gifts) (lit.)

et al., 2000, p. 57). It has been proposed that inhibition is closely related to WM as age differences in WM functioning primarily reflect individual differences in inhibition abilities (e.g., Hasher & Zacks, 1988). Inhibition is crucial for effective language production, enabling the speaker to suppress distracting information, such as nontarget lexical representations, which compete with the target lexical representation for selection. The lexical representations that must be suppressed can be phonologically or semantically related to the target representation. The role of inhibition has been explored in aspects of language production such as the tip-of-the-tongue (TOT) states and VRMP.

TOT states are situations in which the speaker has access to the semantic and (morpho)syntactic information of the word that they want to produce (i.e., they have activated and selected the lemma representation of the target word; e.g., Levelt, 1989), but they have difficulty retrieving the corresponding phonological form (a.k.a. lexeme). Older adults experience TOT states more frequently than younger adults (Burke & Shafto, 2004). It has been found that, when the speaker has alternate words in mind, that is, words that are phonologically related to the target word, they are less likely to resolve the TOT states than when they have no alternate words in mind (Brown & Nix, 1996; but see Burke & Shafto, 2004). Moreover, even when the TOT states are resolved, retrieving the target word takes longer when the speaker has alternate words in mind than when they have not, and this delay is longer in older adults than in younger adults (Abrams & Davis, 2016). The findings above suggest that inhibition might play a role in the resolution of TOT states. The fact that it takes longer older adults than younger adults to resolve TOT states when they have alternate words in mind aligns with the decline in our ability to suppress distracting information as we age (e.g., Bedard et al., 2002; Kane, Hasher, Stoltzfus, Zacks, & Connelly, 1994; Lustig, Hasher, & Zacks, 2008; Williams, Ponesse, Schachar, Logan, & Tannock, 1999).

Inhibition subserves not only the resolution of TOT states but also the execution of standard constrained laboratory tasks tapping VRMP, such as transformational sentence completion tasks tapping production of verb-related morphosyntactic categories that do not lend themselves to cue-based retrieval interference (e.g., time reference/tense and grammatical aspect). In these tasks, participants hear a source sentence (e.g., *Yesterday John ate salmon*) and the beginning of a target sentence (e.g., *Tomorrow John* ____________), which they are required to complete by producing a different form of the verb phrase that appears in the source sentence (i.e., *will eat salmon*). To successfully complete the target sentence, one must inhibit the value of the relevant feature encoded in the verb form included in the source sentence. For instance, in the above example, the relevant feature encoded in the verb form that appears in the source sentence is TENSE, and the value for this feature is PAST. To correctly complete the lead-in sentence above, the participant must inhibit a response that encodes PAST. Evidence that inhibition is critically involved in transformational sentence completion tasks tapping production of time reference/tense has been provided by Ibbotson and Kearvell-White (2015), who tested 81 children (*Mean Age* = 5;6 years; *SD* = 3.54) with language and cognitive tasks. They found that individual variation in inhibition (measured with the Stroop task) predicted participants' ability to produce target past-tensed verbs in a picture-assisted transformational sentence completion task (e.g., *This boy is walking. He walks everyday. Yesterday he* _________*?*).

1.2. Role of demographic factors, cognitive capacities, locality, and morphosyntactic category in language production

1.2.1. Age effects

In healthy adults, age affects aspects of language production such as lexical retrieval and discourse production. For example, verbal fluency decreases with age (Ardila & Rosselli, 1989), and young adult speakers outperform older speakers in picture naming tasks in terms of both accuracy and speed of lexical retrieval (for a review, see Mortensen, Meyer, & Humphreys, 2006). Similarly, in studies using definition naming tasks, young adults experience fewer TOT states compared to older adults (e.g., Brown & Nix, 1996; Burke & Shafto, 2004; Mortensen et al., 2006). These lexical retrieval problems have been attributed to age-related weakening of the connections linking lemmas (i.e., semantic and morphosyntactic representations of words) to phonological word forms (Mortensen et al., 2006) and/or to age-related decline in the ability to inhibit the activation of nontarget word forms that are phonologically related to the target word (see, e.g., Zacks & Hasher, 1994). In discourse production, older speakers tend to be more verbose and less fluent than younger speakers. This could stem from a general difficulty inhibiting irrelevant information or from language-specific deficits that affect lexical retrieval and/or the planning of syntactic structure and content in their utterances (e.g., Mortensen et al., 2006). Moreover, older speakers often produce discourse that is less coherent and sentences that are structurally less complex compared to younger adults (Marini, Boewe, Caltagirone, & Carlomagno, 2005).

While several studies have explored the effects of aging on lexical retrieval and discourse production, our understanding of the role of age in morphosyntactic production in adult speakers remains limited. Sung (2015) tested 60 neurotypical Korean-speaking adults aged between 21 and 86 years and found a strong negative effect of age on the production of noncanonical sentences in a syntactic-priming task. Marini et al. (2005) analyzed narratives of 69 neurotypical Italian-speaking adults aged between 20 and 84 years, and found that morphosyntactic errors (termed in their study as *paragrammatisms*) increased with age. However, the authors did not break down paragrammatisms into verb-related morphosyntactic errors and nominal-domain morphosyntactic errors; therefore, it is not clear whether there was an age-related decline in VRMP. In another study exploring the impact of aging on language production, Kynette and Kemper (1986) analyzed samples of semispontaneous speech from 32 neurotypical English-speaking middle-aged and older participants (aged 50–89 years), and found that participants in their 70s and 80s made more tense errors compared to those in their 50s and 60s. More recently, Fyndanis, Arcara et al. (2018) reported a significant age effect on the accuracy performance of 103 Greek-speaking neurotypical adults in a sentence completion task tapping production of time reference, grammatical aspect, and subject-verb agreement; accuracy performance on VRMP dropped with age. However, the authors did not address whether the relationship between age and VRMP was mediated by verbal WM capacity, which also affected VRMP. Since, in adult speakers, cognitive functions supporting language production (e.g., WM, attention, SOP, and executive functions such as inhibition and set-shifting) decline with age (for a review, see Calabria, 2023), it appears that the effect of aging on several aspects of language production is indirect and not direct (Burke & Shafto, 2008; Calabria, 2023). This is consistent with Salthouse's (2013) view that "age is not a causal variable, but instead is best conceptualized as a continuum along which causal factors operate" and "[t]he goal of many developmental researchers has therefore been to identify causal factors that could be used to replace the age variable in explanations" (p. 129). Cognitive functioning, broadly construed, encompasses not only WM, STM, SOP, and inhibition, which are relevant here, but also VRMP. Salthouse's (2013) view of age might also apply to education. That is, it might be that education only indirectly affects VRMP (see Section 1.2.2).

1.2.2. Education effects

It appears that not only age, but also education plays an important role in aspects of language production. For example, Simos, Kasselimis, and Mouzaki (2011), in a study on 500 Greek-speaking community-dwelling adults aged between 50 and 84 years, reported stronger education effects on expressive vocabulary than age effects. Educational level also affects verbal fluency (e.g., Rosselli, Ardila, & Rosas, 1990) and aspects of narrative production. Ardila and Rosselli (1996), for example, administered a picture description task (Cookie Theft; Goodglass & Kaplan, 1972) to 180 neurotypical individuals, aged between 16 and 65 years and varying in educational level. One key finding was that educational level significantly predicted the amount of language produced to describe the picture: participants with higher educational levels produced a larger total number of words during the task.

Little is known about the effect of education on VRMP. In a study on 80 neurotypical Greek-speaking middle-aged and older individuals (*Age Range*: 55–67 years) who varied in years of formal education (*Mean* = 13.1 years of education; *SD* = 4.5 years of education; *Range* = 6–22 years of education), Fyndanis et al. (2022) reported a significant main effect of education on participants' accuracy performance in a sentence completion task tapping VRMP. The more the participants' years of formal education, the better their accuracy performance on production of grammatical aspect, time reference, and subject-verb agreement. In Fyndanis et al.'s (2022) study, education did not interact with production of these morphosyntactic categories. Yet, there was a significant interaction between education and VRMP in local versus nonlocal configurations: education positively affected VRMP more in local than in nonlocal configurations (for examples of such configurations, see Section 1.1.2 and Table 1). The authors accounted for these results by proposing that years of formal education is a proxy for the efficiency of a procedural memory system that supports aspects of language production such as VRMP. This procedural system might be LTWM for language (Caplan & Waters, 2013). As mentioned in Section 1.1.3, LTWM is a WM system based on storage in long-term memory, and supports skilled activities (Ericsson & Kintsch, 1995); language is a skilled activity (Caplan & Waters, 2013). Fyndanis et al. (2022) based their proposal on the fact that educational level is considered to be a proxy for language experience, including experience in formal testing situations (Ostrosky-Solis, Ardila, Rosselli, Lopez-Arango, & Uriel-Mendoza, 1998; Simos et al., 2011), as "a higher educational level produces more exposure to written language and possibly a greater metalinguistic knowledge" and "individuals with a higher educational level may tend to read more and to engage in conversations about a wider range of topics later on in their life compared to people with a lower educational level" (Fyndanis et al., 2022, p. 5). On the assumption that educational level largely determines the degree of linguistic experience, it could be taken as a proxy for language skill. A related assumption is that, the greater the language experience, the stronger the connections in the language network hosted in long-term memory, thereby enhancing the efficiency of the assumed procedural system that supports language production. Of note, Fyndanis et al. (2022) argued that VRMP is supported not only by a procedural memory system, but also by verbal WM, which is a controlled memory system. Finally, they explained the differential effect of education on VRMP in local versus nonlocal configurations by assuming that the procedural memory system supporting VRMP is sensitive to frequency patterns in language and better supports VRMP in more frequent than in less frequent configurations.

1.2.3. Sex effects

The bulk of studies examining the impact of sex on language in adults have focused on lexical knowledge and retrieval, yielding mixed results. Weiss et al. (2003), for example, reported a female advantage in verbal fluency, suggesting that women know a larger number of words compared to men, whereas Tombaugh, Kozak, and Rees (1999) found no difference between men and women in verbal fluency. Simos et al. (2011) found a male advantage in tasks tapping lexical retrieval and comprehension of nouns, verbs, and adjectives.

No significant effect of sex has been reported specifically for verb retrieval (Allendorfer et al., 2012—though Angelopoulou et al. [2020] found that women exhibit a higher verb frequency than men in discourse production).

The relationship between sex and aging concerning language production is understudied. Ardila and Rosselli (1996) found that age-related decline in the amount of spontaneous speech interacts with sex, with aging affecting male neurotypical adults more than female neurotypical adults. Furthermore, Moscoso del Prado Martín (2017) reported evidence suggesting that sex interacts with age regarding the diversity of syntactic structures produced in natural conversations. Specifically, he found that while men exhibit a reduction in the diversity of syntactic structures starting at the age of 45, no such reduction is observed in women at least until their early 60s. However, in the same study, no interaction between sex and age was found concerning the diversity of inflected word forms produced in natural conversations; both women and men exhibited an increasing pattern up to the age of 45, after which the diversity of inflected forms began to decrease in both sexes. It remains unclear whether there is an effect of sex on accuracy performance on VRMP, or whether sex modulates the relationship between age and neurotypical adults' VRMP performance. For instance, to the best of our knowledge, no study has hitherto addressed whether a potential age-related decline in the production of time reference and grammatical aspect interacts with sex.

1.2.4. Effects of cognitive capacities

Not only the above variables, but also cognitive capacities that decline with age seem to affect aspects of language processing such as VRMP. Studies on cue-based retrieval interference, for example, have provided evidence that WM supports the production of subject-verb agreement (e.g., Hartsuiker & Barkhuysen, 2006; Slevc & Martin, 2016). Cue-based retrieval interference is involved in sentences such as *The key to the cabinets is/*are on the table*, as the words *key* and *cabinets* match cues derived from the verb, which may give rise to subject-verb agreement errors (e.g., Bock & Cutting, 1992; Bock & Miller, 1991). Agreement attraction errors are more likely to occur when the noun/determiner phrase that intervenes between the subject and the verb is semantically closely related to the subject. This is the case, for example, when the intervening noun/determiner phrase (*the cabinets* in the example above) is part of a prepositional phrase (i.e., *to the cabinets*) that modifies the subject noun/determiner phrase (i.e., *the key*) (e.g., Solomon & Pearlmutter, 2004). Slevc and Martin (2016, p. 773) argued that "producing an agreeing verb involves a cue-based search in WM for an appropriate controlling noun, which is subject to interference from other elements in memory with similar properties." For instance, in the sentence *The key to the cabinets *are on the table*, the participant had to encode in the verb the NUMBER value carried by the subject noun/determiner phrase *the key* (i.e., SINGULAR). Nevertheless, the NUMBER value of the intervening noun/determiner phrase *the cabinets* (i.e., PLURAL) interfered with the NUMBER value of the subject noun/determiner phrase *the key* (i.e., SINGULAR), resulting in an agreement attraction error (i.e., production of the verb form *are* instead of *is*).

WM has been found to be involved in VRMP even in contexts that do not involve cue-based retrieval interference. In a study on Dutch agrammatic aphasia, for example, Kok et al. (2007) found that taxing WM leads to worse performance on the production of time reference/tense and subject-verb agreement. These categories were tested with a sentence completion task, in which participants were presented with written sentences with a missing verb, and with the infinitival form of this verb (e.g., *Het meisje _____ tegenwoordig vaak de vloer* [*dweilen*], The girl _____ nowadays often the floor [to mop] [lit.]). Participants were instructed to read aloud the sentence producing the missing finite verb form. As can be seen in the above example, both the temporal adverbial (*tegenwoordig*) and the subject (*het meisje*) were adjacent to the space indicating the missing verb. In a more recent study on Greek healthy aging and aphasia, Fyndanis, Arcara et al. (2018) found that verbal WM affects production of time reference, grammatical aspect, and subject-verb agreement in contexts that do not involve or favor cue-based retrieval interference. These categories were tested with a sentence completion task, in which all the lead-in sentences consisted of a temporal adverbial (adverb phrase), an aspectual adverbial (prepositional phrase), and a subject noun/determiner phrase, which encoded different features (TENSE, ASPECT, and PERSON/NUMBER, respectively). The authors also found that verbal WM affected aspect more than time reference and agreement, and time reference more than agreement.

In a follow-up study on Greek-speaking neurotypical middle-aged/older adults, Fyndanis et al. (2022) sought to replicate Fyndanis, Arcara et al.'s (2018) findings regarding the role of verbal WM in production of grammatical aspect, time reference, and subject-verb agreement, and also investigated the role of nonverbal WM, verbal STM, nonverbal STM, SOP, and LTWM for language in VRMP. They used the sentence completion task employed by Fyndanis, Arcara et al. (2018), and cognitive tasks measuring verbal STM capacity, nonverbal STM capacity, verbal WM capacity, nonverbal WM capacity, and SOP. Moreover, they took years of formal education as a proxy for language skill and experience, which might determine the efficiency of LTWM for language. Fyndanis et al. (2022) found that verbal WM plays a role in VRMP, affecting aspect and time reference more than agreement, which is in line with Fyndanis, Arcara et al. (2018). However, in Fyndanis et al. (2022), verbal WM comparably affected aspect and time reference, which is at odds with Fyndanis, Arcara et al. (2018). Fyndanis et al. (2022) also reported significant main effects of verbal STM and education. Taken together, these results were interpreted as suggesting that VRMP is supported by both the processing and storage components of verbal WM, as well as by LTWM for language. The fact that there were main effects of verbal STM and verbal WM but no main effects of nonverbal STM and/or nonverbal WM was taken to suggest that VRMP is predominantly supported by domain-specific, not domain-general, memory resources.

The role of SOP in sentence production has been explored to a lesser extent. SOP has been found to affect sentence planning (Kemper et al., 2011). Moreover, impaired morphosyntactic production in children with specific language impairment has been partly attributed to reduced SOP (Leonard, 1998, 2014). Nevertheless, Fyndanis et al.'s (2022) study on neurotypical Greek-speaking adults reported no significant main effect of SOP on production of tense, grammatical aspect, and subject-verb agreement. In the same study, however, SOP was moderately correlated with participants' accuracy performance on the production of the two most demanding morphosyntactic categories under investigation (i.e., aspect and tense). The lack of a significant main effect of SOP in that study could be attributed to its inclusion alongside seven other variables in the fixed structure of a linear mixed-effects model, despite the relatively small sample size ($N = 80$). A study with greater statistical power may reveal a significant main effect of SOP on VRMP.

1.2.5. Morphosyntactic category and locality effects

There is evidence that accuracy performance on VRMP largely depends on the morphosyntactic category/categories under study. For example, Fyndanis and collaborators investigated the production of grammatical aspect, time reference, and subject-verb agreement in Greek agrammatic aphasia (Fyndanis et al., 2012; Fyndanis, Arcara et al., 2018), in Greek DAT (Fyndanis et al., 2013), in Greek multiple sclerosis (Fyndanis et al., 2020), and in Greek-speaking neurotypical individuals sampling almost the entire adult age range (Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022), and found that all four populations fared worse on aspect than on time reference and agreement. Moreover, aspect and time reference were more impaired than agreement in all the above populations except for individuals with multiple sclerosis. It appears, therefore, that both grammatical aspect and time reference are demanding morphosyntactic categories, with aspect taxing the processing system more than time reference.

The evidence about the role of locality in accuracy performance in tasks tapping VRMP is inconclusive. While Fyndanis, Arcara et al. (2018) found no effects of locality in the production of time reference, grammatical aspect, and subject-verb agreement, Fyndanis et al. (2022) found locality to affect VRMP, with nonlocal configurations eliciting worse performance than local configurations. Additionally, in Fyndanis et al. (2022), locality affected subject-verb agreement and grammatical aspect but not time reference. The authors assumed that this interaction might reflect the statistical distribution of local versus nonlocal grammatical aspect, subject-verb agreement, and time reference in Greek. Locality also interacted with education, as the latter affected VRMP more in local than in nonlocal configurations. To account for this finding, Fyndanis et al. (2022) suggested that LTWM for language (for which education was taken as a proxy) might be sensitive to frequency patterns in language and better supports VRMP in more frequent than in less frequent configurations. The relationship between locality and education was not modulated by the three morphosyntactic categories.

1.2.6. Summary of findings about VRMP in neurotypical adults

In sum, although there is some evidence for a role of verbal WM in VRMP in healthy aging (Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022), the findings about the role of locality are inconclusive. Additionally, it is still unknown whether sex and inhibition affect participants' performance on sentence completion tasks tapping VRMP. Lastly, the previous findings that age, education, and verbal STM affect VRMP (Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022), but SOP does not (Fyndanis et al., 2022), need to be replicated.

2. The present study

The current study follows up on Fyndanis et al. (2022) and Fyndanis, Arcara et al. (2018) and explores the role of demographic factors (age, education, and sex), cognitive capacities (verbal WM, verbal STM, SOP, and inhibition), and locality (task/material-related variable) in the production of time reference and grammatical aspect. The study also seeks to replicate the dissociation between time reference and aspect, reported for both neurotypical adults (Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022) and neurologically affected adults (Fyndanis et al., 2012, 2013, 2020; Fyndanis, Arcara et al., 2018).

We address the following research questions and make the following predictions:

(1) *Does locality interact with any of the memory systems examined here*, *namely*, *verbal WM, verbal STM, and LTWM for language (as reflected in years of formal education)?*

Based on Fyndanis et al. (2022), we expect a significant interaction between locality and LTWM for language to emerge.

(2) *(a). Which demographic, cognitive, and task/material-related factors play a role in VRMP? (b) Relatedly, is VRMP supported by both the storage and processing components of verbal WM? (c) Is VRMP supported by both verbal WM and LTWM for language? (d) Do grammatical aspect and time reference dissociate, with more errors occurring in the former than in the latter?*

Based on previous work by Fyndanis and colleagues (Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022), we expect to find significant main effects of verbal WM, verbal STM, education/LTWM for language, and age. If this prediction is borne out, the answer to questions (2b) and (2c) will be positive. Given the contradictory findings regarding the role of locality in VRMP (Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022), no prediction can be made about locality in terms of significant main effects. We also expect to find significant main effects of inhibition and SOP, as both cognitive capacities have been argued to be major determinants of WM functioning (e.g., Fry & Hale, 1996, 2000; Hasher & Zacks, 1988; Salthouse, 1992). Moreover, in Fyndanis et al. (2022), SOP was moderately correlated with participants' accuracy performance on the production of grammatical aspect and time reference. Furthermore, inhibition should be critically involved in transformational sentence completion tasks (see background information about inhibition in Section 1.1.3). We also expect participants to make more aspect errors than time reference errors, which would replicate previous findings from healthy aging (Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022), agrammatic aphasia (Fyndanis et al., 2012; Fyndanis, Arcara et al., 2018), DAT (Fyndanis et al., 2013), and multiple sclerosis (Fyndanis et al., 2020).

(3) *Do any of the variables yielding significant main effects interact with the production of time reference and grammatical aspect?*

No prediction can be made about the interaction between verbal WM and VRMP, as previous results are mixed (Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022). We expect, however, to replicate Fyndanis et al.'s (2022) finding that locality affects grammatical aspect but not time reference, and also predict no interactions between education and VRMP or between verbal STM and VRMP, which would also be consistent with Fyndanis et al. (2022).

(4) *Is there a female advantage in VRMP? Relatedly, is the relationship between age and VRMP modulated by sex?*

This question was motivated by the fact that most studies exploring the role of sex in language production have provided evidence for a female advantage (e.g., Ardila & Rosselli, 1996; Angelopoulou et al., 2020; Moscoso del Prado Martín, 2017; Weiss et al., 2003). Ardila and Rosselli (1996), for example, reported an age-related decline in the amount of spontaneous speech interacts with sex, with age affecting healthy male adults more than healthy female adults; and Moscoso del Prado Martín (2017) found that women are better sheltered from age-related reduction in the diversity of syntactic structures produced in natural conversations, compared to men. Nevertheless, to the best of our knowledge, it is still unknown whether the "female advantage" extends to the age-related decline of VRMP in neurotypical adult individuals.

3. Methods

3.1. Participants

Two hundred neurotypical Greek-speaking adults (138 women) differing in age (*Age Range* = 19–80; *Mean Age* = 40,1; *SD* = 15.4) and years of formal education (*Range* = 6–24; *Mean* = 15; *SD* = 3) participated in the study. The distribution of participants across lifespan decades is presented in Fig. 1. All older participants (≥60 years old) were administered a validated Greek version of the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) to exclude those with potential cognitive impairments. To this end, we adopted the cut-off scores for MoCA performance proposed by Poptsi et al. (2019) for

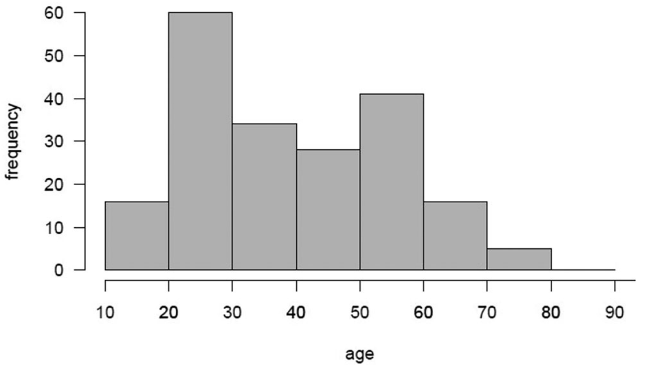

Fig. 1. Distribution of participants across lifespan decades (x-axis: age range separated in 10-year bins; y-axis: number of observations).

Greek older adults: all included participants with ≤6 years of formal education scored ≥23 (out of 30) on MoCA, whereas participants with ≥7 years of formal education scored ≥26.

Participants were recruited using convenience sampling (i.e., through the social, work, and family networks of the authors) and, occasionally, using snowballing sampling. All participants were informed in advance about the scope, the duration, and the procedure of the study. Before participating, they all signed a consent form. The research procedures were in accord with all APA ethical guidelines. The research was approved by the Norwegian Centre for Research Data AS and from the Research Ethics Committee of the National and Kapodistrian University of Athens.

3.2. Materials

Participants completed a novel sentence completion task and a series of standard cognitive tasks measuring verbal WM capacity (digit backward span task and digit ordering span task), verbal STM capacity (digit forward span task), SOP (string of letters comparison task and box completion task), and inhibition (verbal Stroop task).

3.2.1. Sentence completion task

The sentence completion task tested participants' ability to produce time reference and grammatical aspect in local and nonlocal configurations. Participants were auditorily presented with a source sentence (e.g., *Mésa se misí óra aftós xθés mírase ta ðóra*. Within half an hour he yesterday distributed-PERFECTIVE the gifts [lit.]) and the beginning of a target sentence (e.g., *Epí misí óra aftós ávrio…* For half an hour he tomorrow…[lit.]). They were instructed to complete the target sentence producing the correct form of the verb phrase included in the source sentence (i.e., *…θa mirázi ta ðóra* …will distribute-IMPERFECTIVE the gifts [lit.]). (For more examples, see Table 1). All sentences followed the same structure: aspectual or temporal adverbial + (animate) subject + temporal or aspectual adverbial + verb + (inanimate) object (see Table 1). Therefore, all lead-in sentences (i.e., preverbal material in target sentences) consisted of a subject, an aspectual adverbial, and a temporal adverbial. Both adverbials served as critical cues, as the source sentence and the target sentence always differed in *both* the temporal and aspectual contexts/adverbials (see Table 1). The participant, therefore, had to perform a "dual transformation" of the verb form appearing in the source sentence: the target verb form required encoding of different time reference *and* aspectual values than those encoded on the verb of the source sentence. Thus, each item tested both time reference and aspect, which is a novel feature of the task; in most sentence completion tasks, each item belongs to a single condition and tests one morphosyntactic category only (e.g., Friedmann & Grodzinsky, 1997; Fyndanis et al., 2012; Fyndanis, Arcara et al., 2018; Gavarrò & Martínez-Ferreiro, 2007; Nanousi et al., 2006; Protopapas et al., 2016; Varlokosta et al., 2006; Wenzlaff & Clahsen, 2004).

Twelve disyllabic, regular verbs taking two arguments (i.e., a subject and an object), all stressed on the penultimate syllable, were used to create 96 experimental "dual-condition items." Thus, as mentioned above, each experimental item tested both time reference and grammatical aspect. Moreover, either morphosyntactic category was tested in both local and nonlocal configurations. Overall, there were 48 local time reference items, 48 nonlocal time reference items, 48 local grammatical aspect items, and 48 nonlocal grammatical aspect items. Each verb appeared eight times in the 96 "dual-condition items," that is, four times in each of the above four subconditions. Since the same verbs were included in all four morphosyntactic subconditions, the different (sub)conditions were fully matched on all potentially relevant variables (e.g., target verbs' argument structure, subcategorization frame, word length, phonological complexity, frequency, age of acquisition). To facilitate future replication studies, we provide the list of the verbs used in the Appendix.[1]

The experimental "dual-condition items" were divided into four lists of 24 items. The four subconditions above were evenly distributed within each list. Sentences were pseudorandomized within lists, and the item order was kept constant for all participants. Each verb appeared twice in each list, but never twice in the same subcondition in each list. Participants were administered one list each.

The dependent variable of the task was accuracy. Given that the task consisted of "dual-condition items," the verb form produced by the participant in each experimental item was scored along two dimensions, acquiring thus two different scores: one for time reference and one for grammatical aspect.[2]

3.2.2. Cognitive tasks

<u>*Verbal Working Memory*</u> <u>(WM)</u>: To measure participants' verbal WM capacity, we used a digit ordering span task and a digit backward span task. Both complex span tasks involve storage and processing components (e.g., Francis, Clark, & Humphreys, 2003; Nittrouer, Lowenstein, Wucinich, & Moberly, 2016) and are often used to measure verbal WM capacity.

In the digit ordering span task, participants were auditorily presented with sequences of digits—one sequence at a time (e.g., 2, 8, 5, 4)—at a rate of one digit per second and they were instructed to immediately report the digits back in ascending numerical order (i.e., 2, 4, 5, 8). The task included five levels of difficulty, which ranged from two to six digits. Each level consisted of three series of digits of equal length. Scoring was based on the number of correctly remembered digit sequences (one point for each correctly remembered sequence). There was no penalty for wrong answers (maximum score = 15, minimum score = 0).

In the digit backward span task, again, participants heard sequences of digits (e.g., 5, 9, 2, 6) at a rate of one digit per second, but this time they were required to immediately report them back in reverse order of presentation (i.e., 6, 2, 9, 5). The first trial consisted of two digits and the level of difficulty increased up to eight digits. There were, therefore, seven levels of difficulty. Each level consisted of two sequences of digits of equal length. Scoring was based on the number of correctly remembered digit sequences, with no penalty for wrong answers (maximum score = 14, minimum score = 0). To estimate each participant's verbal WM capacity, we computed a composite score based on the two tasks above.

Verbal Short-Term Memory (STM): To measure participants' verbal STM capacity, we used a digit forward span task. In this task, the participant heard sequences of random digits—one sequence at a time—and were instructed to immediately report them back in the same order of presentation. The task included seven levels of difficulty, ranging from two to eight digits. Each level consisted of two equal-length sequences of digits. The score each participant obtained was based on the number of correctly remembered sequences of digits (maximum score = 14, minimum score = 0).

Speed of Processing (SOP): To measure participants' SOP, we used a string of letters comparison task and a box completion task, which assess perceptual speed and sensorimotor speed, respectively (e.g., Salthouse, 1993, 1996). These tasks are considered reliable SOP measures for young and older individuals (Caplan, DeDe, Waters, Michaud, & Tripodis, 2011; Earles et al., 1997; Salthouse & Babcock, 1991).

The string of letters comparison task consisted of 42 pairs of Greek letter sequences (3, 6, or 9 letters in length). In each pair, the letter sequences either differed by one letter or were identical. Participants were instructed to carefully compare the letter sequences of each pair and judge whether they were same or different by writing an *I* (the initial capital letter of the Greek word 'Same') or a ⊿ (the initial capital letter of the Greek word 'Different') on a line between the two strings of letters. They were asked to work as rapidly as they could without skipping any of the pairs. The scoring of the task was based on the number of correct answers provided by the participant in 30 s (maximum score = 42, minimum score = 0).

In the box completion task, participants were presented with an A4 sheet with 10 rows of 10 three-sided squares, and were asked to draw lines closing as many boxes as possible in 30 s. The task was scored based on the number of correctly completed items within the above time limit (maximum score = 100, minimum score = 0). Both SOP tasks were administered in a paper-and-pen format.

Inhibition: To measure participants' inhibition, a Greek version of the multi-item verbal Stroop task (Stroop, 1935) was used. The task consisted of a congruent and an incongruent condition. In each condition, participants were presented with a list of 52 color words (the four Greek color words for "red," "green," "yellow," and "blue") printed in capital letters on a sheet of A4 paper. The color words were arranged in pseudorandom order and were divided into 13 lines (4 items per line). In the congruent condition, all color words matched the color of the ink in which they were printed (e.g., the word "green" was printed in green ink), whereas in the incongruent condition, there was a mismatch between the words and the colors of the letters (e.g., the word "red" was printed in green ink). Participants were presented with each condition separately, with the congruent condition always administered first. They were instructed to *name the colors* horizontally (from left to right) as quickly as possible, focusing only on the ink color of the words and ignoring the color word itself. Their performance in each condition was timed, and any errors in color naming were recorded.

The Stroop task measures inhibition because, in the incongruent condition, which involves interference from two competing streams of information, the participant has to inhibit a more "automatic" process (i.e., reading aloud the words) in order to perform correctly a less automatic task (i.e., naming the colors; e.g., MacLeod & Dunbar, 1988). Inhibiting the more automatic process results in an interference cost, also known as the Stroop effect (Stroop, 1935). We calculated the interference cost as the proportional increase in time (seconds) taken to complete the incongruent condition compared to the congruent condition, using the following formula: *(incongruent condition naming time − congruent condition naming time)/congruent condition naming time*. A lower interference cost implies better inhibition.

3.2.3. Procedure

All participants completed the above tasks in a quiet environment in the following order: (i) transformational sentence completion task; (ii) digit forward span task; (iii) digit ordering span task; (iv) digit backward span task; (v) string of letters comparison task; (vi) box completion task; and (vii) verbal Stroop task. Testing was completed in a single session, which took 50−70 min, including breaks.

It should be noted that, in correlational research, it is common to adhere to a fixed task order (e.g., Boumeester, Michel, & Fyndanis, 2019; Morra & Panesi, 2017; Sorge, Toplak, & Bialystok, 2017) because randomizing task order across participants would introduce an additional source of error variance, which might cause underestimation of the correlations (S. Morra, personal communication, February 9, 2021). Keeping the task order constant across participants ensures that this variable affects all participants similarly. Effects related to task order, such as fatigue or practice effects, if present, act in opposite directions and potentially cancel each other out to some extent. Although task order may influence performance levels on a specific task, it is unlikely to significantly alter the individual differences observed in a given variable.

3.3. Data analysis

Data analysis was performed using R software (R Core Team, 2021, version 4.2.2). We conducted correlational analysis using the Spearman correlation test and fitted generalized linear mixed-effects models (Pinheiro & Bates, 2000) to the data set using the lme4 R package (Bates, Maechler, Bolker, & Walker, 2015, version 1.1.30). For visualizations, we used the jtools R package (Long, 2022, version 2.2.1). Given that accuracy is a dichotomous variable, we used logistic models to predict the probability of correct answers (Jaeger, 2008). Continuous variables were standardized to achieve homogeneity of measurement scales and facilitate the interpretation of interaction terms. Additionally, we performed theoretically motivated path analyses to determine if some significant relationships between an independent variable

Table 2
Descriptive statistics

	Mean (SD)	Min	Max
Aspect	89.6% (13.5%)	45.8%	100%
Local Aspect	91.5% (13.9%)	33.3%	100%
Nonlocal Aspect	87.8% (15.4%)	41.7%	100%
Time Reference	98.4% (4.5%)	66.7%	100%
Local Time Reference	98.6% (4.5%)	66.7%	100%
Nonlocal Time Reference	98.1% (5.7%)	66.7%	100%
Verbal Working Memory	61.9% (10.6%)	28%	90%
Verbal Short-Term Memory	61.3% (14.7%)	5%	100%
Perceptual SOP	9.7 (3.2)	1	19
Motor SOP	15.6 (6.4)	1	37
Inhibition	38.9% (33.3%)	−18%	186%
Education (years)	15 (3)	6	24
Age	40.5 (15.9)	19	80

Abbreviations: SD, standard deviation; SOP, speed of processing.

X and the dependent variable (i.e., accuracy performance on the sentence completion task tapping VRMP) were partially mediated by a variable *Y*.

4. Results

Descriptive statistics are presented in Table 2. Correlations (Spearman rho) between variables are given in Table 3. To investigate whether locality is related to any of the three memory systems under study (i.e., verbal WM capacity, verbal STM capacity, and LTWM for language), we first fitted a model containing three two-way interactions (i.e., Locality × verbal WM capacity, Locality × verbal STM capacity, Locality × LTWM for language/Education) as fixed terms, and subjects and items as random intercepts (Model 1; see Table 4). We also calculated the variance inflation factor (VIF) for all the predictors in Model 1 to detect potential multicollinearity. The VIF values for our model ranged between 1.26 and 2.22, which are deemed acceptable (e.g., Akinwande, Dikko, & Samson, 2015). Therefore, we did not have to remove any variables from the model. Model 1 did not yield any significant interactions between locality and any of the memory systems (Table 4). Subsequently, we fitted Model 1 to a subset of our data set that included only middle-aged and older individuals ($N = 84$, *Age Range* = 45−80, *Mean Age* = 57, *SD* = 8.7, *Education Range [years]* = 6−24, *Mean Education* = 14.1, *SD* = 3.5). This additional analysis was motivated by the fact that Fyndanis et al. (2022), who reported a significant interaction between locality and education/LTWM for language, had only analyzed data of middle-aged and older individuals (≥45 years old). Again, however, no significant interactions emerged (see Table 4).

To investigate whether accuracy performance on VRMP is affected by morphosyntactic category (i.e., grammatical aspect and time reference), locality or any of the cognitive

Table 3
Correlation matrix (r_s)

	Verbal WM	Verbal STM	Perceptual SOP	Motor SOP	Inhibition	Education	Age
Aspect	**0.35 (p<.001)***	**0.29 (p<.001)***	**0.25 (p=.004)***	0.06	**−0.15 (p=.03)***	**0.25 (p<001)***	**−0.27 (p<.001)***
Local Aspect	**0.35 (p<.001)***	**0.24 (p<.001)***	**0.20 (p=.004)***	0.09	**−0.18 (p=.009)***	**0.20 (p=.004)***	**−0.24 (p<.001)***
Nonlocal Aspect	**0.33 (p<.001)***	**0.30 (p<.001)***	**0.27 (p<.001)***	0.06	−0.11	**0.28 (p<.001)***	**−0.26 (p<.001)***
Time Reference	**0.21 (p=.003)***	**0.16 (p=.02)***	**0.17 (p=.02)***	−0.07	−0.07	**0.14 (p=.05)***	**−0.17 (p=.02)***
Local TR	**0.20 (p=.004)***	0.13	**0.15 (p=.03)***	−0.04	−0.08	0.11	−0.05
Nonlocal TR	**0.19 (p=.007)***	**0.15 (p=.03)***	0.10	−0.02	−0.03	**0.14 (p=.05)***	**−0.20 (p=.004)***
Morphosyntactic Production Total	**0.39 (p<.001)***	**0.32 (p<.001)***	**0.29 (p<.001)***	0.07	−0.18	**0.27 (p<.001)***	**−0.29 (p<.001)***
Morph Prod Local	**0.38 (p<.001)***	**0.26 (p<.001)***	**0.24 (p<.001)***	0.08	**−0.20 (p=.006)***	**0.21 (p=.003)***	**−0.23 (p<.001)***
Morph Prod Nonlocal	**0.37 (p<.001)***	**0.33 (p<.001)***	**0.29 (p<.001)***	0.08	**−0.15 (p=.04)***	**0.31 (p<.001)***	**−0.30 (p<.001)***
Verbal WM		**0.58 (p<.001)***	**0.31 (p<.001)***	**0.14 (p=.04)***	**−0.37 (p<.001)***	**0.17 (p=.02)***	**−0.23 (p<.001)***
Verbal STM			**0.36 (p<.001)***	**0.21 (p=.003)***	**−0.17 (p=.02)***	**0.16 (p=.02)***	**−0.18 (p=.01)***
Perceptual SOP				**0.36 (p<.001)***	**−0.29 (p<.001)***	**0.36 (p<.001)***	**−0.49 (p<.001)***
Motor SOP					**−0.15 (p=.04)***	**0.29 (p<.001)***	**−0.20 (p=.006)***
Inhibition						**−0.20 (p=.005)***	**0.24 (p<.001)***
Education							**−0.14 (p=.05)***

Note. The symbol * indicates significant correlations.
Abbreviations: SOP, speed of processing; STM, short-term memory; TR, time reference; WM, working memory.

Table 4
Generalized linear mixed-effect Model 1

	Estimate	Std. Error	*z*-value	*Pr* (> | z |)
Model 1 fitted to full data set				
Intercept (Locality = Local)	3.792	0.143	26.428	**< 0.001***
Locality = Nonlocal	−0.458	0.103	−4.432	**< 0.001***
Verbal WM capacity	0.516	0.142	3.637	**<0.001***
Verbal STM capacity	0.194	0.14	1.391	0.164
Education	0.273	0.113	2.417	**0.02***
Locality = Nonlocal: verbal WM capacity	−0.151	0.107	−1.414	0.157
Locality = Nonlocal: verbal STM capacity	0.029	0.105	0.278	0.781
Locality = Nonlocal: Education	0.059	0.083	0.719	0.472
Model 1 fitted to subset of middle-aged and older participants				
Intercept (Locality = Local)	3.51	0.202	17.361	**< 0.001***
Locality = Nonlocal	−0.483	0.152	−3.179	**0.001***
Verbal WM capacity	0.299	0.137	2.175	**0.007***
Verbal STM capacity	0.52	0.195	2.674	0.882
Education	0.032	0.216	0.149	0.03*
Locality = Nonlocal: verbal WM capacity	−0.098	0.145	−0.674	0.501
Locality = Nonlocal: verbal STM capacity	0.122	0.168	0.725	0.468
Locality = Nonlocal: Education	−0.036	0.099	−0.361	0.718

Note. Model 1 included the two-way interactions between (1) Locality (two levels: Local, Nonlocal) and Verbal Working Memory (WM) Capacity (continuous variable), (2) Locality and Verbal Short-Term Memory (STM) Capacity (continuous variable), and (3) Locality and (years of formal) Education (continuous variable) as fixed terms, as well as Subjects and Items as random intercepts. The symbol * indicates significant effects.

capacities and demographic factors considered here, we first fitted a model that included Morphosyntactic Condition (categorical variable with two levels: Aspect, Time Reference), verbal WM capacity (continuous variable), verbal STM capacity (continuous variable), Perceptual SOP (continuous variable), Motor SOP (continuous variable), Inhibition (continuous variable), (years of formal) Education/LTWM for language (continuous variable), Age (continuous variable), Sex (categorical variable with two levels: Female, Male), and Locality (categorical variable with two levels: Local, Nonlocal) as fixed terms, and subjects and items as random intercepts. We then fitted the same model adding Morphosyntactic Condition as by-subject random slope. Based on the Akaike Information Criterion (AIC; Burnham & Anderson, 2004), the model with Morphosyntactic Condition as by-subject random slope (Model 2) outperformed the model without random slopes. The VIF values of the predictors included in Model 2 ranged from 1 to 1.97, which are considered acceptable values. Thus, no variables were removed from this model.

Results showed significant main effects of Morphosyntactic Condition (more errors occurred in aspect than in time reference), Locality (more errors occurred in nonlocal than in local configurations), verbal WM (the greater the participants' verbal WM capacity, the better their accuracy performance on VRMP), Motor SOP (the slower the motor SOP, the better the accuracy performance on VRMP), Education/LTWM for language (the higher the participants' education level/the more efficient the participants' LTWM for language, the better their

Table 5
Generalized linear mixed-effect Model 3

	Estimate	Std. Error	z-value	$Pr (> \| z \|)$
Model 3				
Intercept (Morphosynt. Cond. = Aspect; Locality = Local)	3.307	0.161	20.589	**< 0.001***
Morphosynt. Cond. = Time Reference	2.63	0.34	7.743	**< 0.001***
Locality = Nonlocal	−0.466	0.113	−4.122	**< 0.001***
Verbal WM capacity	0.549	0.112	4.914	**< 0.001***
Motor SOP	−0.237	0.116	−2.053	**0.04***
Education	0.309	0.113	2.723	**0.006***
Age	−0.393	0.112	−3.508	**<0.001***

Note. Model 3 included the additive effect of Morphosyntactic Condition, Locality, Verbal Working Memory (WM) Capacity, Motor Speed of Processing (SOP), (years of formal) Education, and Age. Model 3 also included Subjects and Items as random intercepts, and Morphosyntactic Condition as by-subject random slope. The symbol * indicates significant effects.

performance on VRMP), and Age (the younger the participants, the better their performance on VRMP). Model 2's results showed no significant main effects of verbal STM ($\beta = 0.2$; $SE = 0.134$; z-value $= 1.489$; $p = .137$), perceptual SOP ($\beta = 0.145$; $SE = 0.143$; z-value $= 1.009$; $p = .303$), inhibition ($\beta = 0.142$; $SE = 0.116$; z-value $= 1.226$; $p = .22$), and sex ($\beta = -0.241$; $SE = 0.228$; z-value $= -1.056$; $p = .291$). The output of Model 2 is presented in Table S1 (see Supplementary Materials). We then fitted two models that included only the variables showing significant main effects in Model 2 as fixed terms (i.e., Morphosyntactic Condition, Locality, verbal WM, Motor SOP, Education, and Age). Both models included subjects and items as random intercepts, but one of them also included Morphosyntactic Condition as a by-subject random slope. Again, based on AIC, the model with the random slope (Model 3) outperformed the model without the random slope. All predictor variables that showed significant main effects in Model 2 remained significant in Model 3 (Table 5). Overall, participants performed better on time reference than on grammatical aspect, and better in local than in nonlocal configurations (Fig. 2).

To explore whether VRMP significantly interacted with locality, verbal WM capacity, motor SOP, education/LTWM for language or age—variables which all yielded significant main effects in Model 3 (Table 5)—we fitted a model including the interactions between Morphosyntactic Condition (two levels: Time Reference and Aspect) and each of the above predictor variables as fixed terms, and subjects and items as random effects. We then fitted the same model adding Morphosyntactic Condition as by-subject random slope. We selected the best model based on AIC (see Model 4; Table 6). The model revealed no interactions between Morphosyntactic Condition and any of the above predictor variables.

Lastly, to investigate whether age-related decline in participants' performance on VRMP is modulated by sex, we fitted a model including a two-way interaction between sex and age as its fixed term, and subjects and items as random effects (Model 5, Table 7). This interaction was not significant.

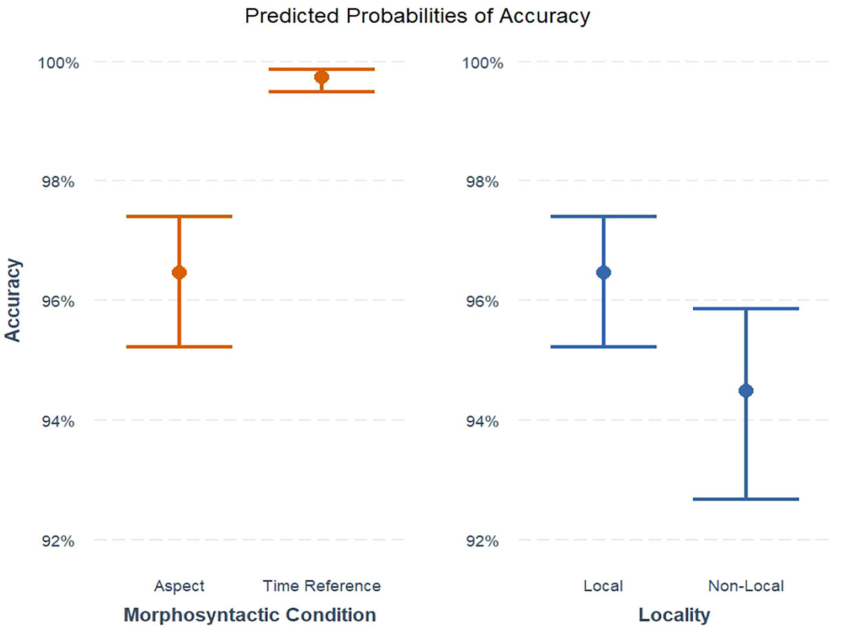

Fig. 2. Left: Participants' estimated percent correct mean performance and standard error (SE) on production of grammatical aspect and time reference (with local and nonlocal configurations collapsed) based on Model 3. Right: Participants' estimated percent correct mean performance and SE on morphosyntactic production (with aspect and time reference collapsed) in local and nonlocal configurations based on Model 3.

Table 6
Generalized linear mixed-effect Model 4

	Estimate	Std. Error	*z*-value	*Pr* (> | z |)
Intercept (Morphosynt. Cond. = Aspect; Locality = Local)	3.324	0.170	19.543	**< 0.001***
Morphosynt. Cond. = Time Reference	2.564	0.411	6.24	**< 0.001***
Locality = Nonlocal	−0.499	0.149	−3.339	**< 0.001***
Verbal WM capacity	0.529	0.123	4.287	**< 0.001***
Motor SOP	−0.181	0.126	−1.434	0.152
Education	0.326	0.125	2.611	**0.009***
Age	−0.401	0.123	−3.266	**0.001***
Morphosynt. Cond. = Time Referene: Locality = Nonlocal	0.112	0.338	0.333	0.739
Morphosynt. Cond. = Time Reference: verbal WM capacity	0.088	0.23	0.383	0.702
Morphosynt. Cond. = Time Reference: Motor SOP	−0.25	0.246	−1.015	0.310
Morphosynt. Cond. = Time Reference: Education	−0.071	0.236	−0.299	0.765
Morphosynt. Cond. = Time Reference: Age	0.03	0.242	0.125	0.901

Note. Model 4 included the two-way interactions between (1) Morphosyntactic Condition (two levels: Aspect, Time Reference) and Locality (two levels: Local, Nonlocal), (2) Morphosyntactic Condition and Verbal Working Memory (WM) Capacity (continuous variable), (3) Morphosyntactic Condition and Motor Speed of Processing (SOP), (4) Morphosyntactic Condition and (years of formal) Education (continuous variable), (5) Morphosyntactic Condition and Age (continuous variable) as fixed terms, Subjects and Items as random intercepts, and Morphosyntactic Condition as by-subject random slope. The symbol * indicates significant effects.

Table 7
Generalized linear mixed-effect Model 5

	Estimate	Std. Error	*z*-value	*Pr* (> | z |)
Intercept (Sex = Female)	3.59	0.155	23.185	**< 0.001***
Sex = Male	−0.569	0.133	−4.29	0.553
Age	−0.14	0.237	−0.593	**< 0.001***
Sex = Male: Age	0.164	0.227	0.721	0.471

Note. Model 5 included the two-way interaction between Sex (two levels: Female, Male) and Age (continuous variable) as fixed terms and Subjects and Items as random intercepts. The symbol * indicates significant effects.

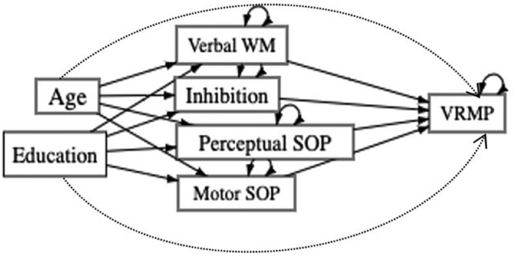

Fig. 3. The path diagram illustrates the direct effects of age and education on verb-related morphosyntactic production (VRMP) (dotted lines), as well as the mediating effects of verbal working memory (WM), inhibition, perceptual speed of processing (SOP), and motor SOP on VRMP (solid lines).

We also performed path analysis in Structural Equation Modeling to examine the direct and indirect relationships among variables in theoretically motivated models and to explore complex patterns of associations in our data set. Path analysis allows modeling of mediation effects by estimating the direct effect(s) of the independent variable(s) on the dependent variable, the direct effect(s) of the independent variable(s) on the mediator(s), and the direct effect(s) of the mediator(s) on the dependent variable. By examining these paths simultaneously, we can assess the total effect(s) (direct plus indirect) of the independent variable(s) on the dependent variable and determine the effect(s) of the mediator(s) on the dependent variable.

We constructed two sets of path models and tested them on the VRMP data set (which includes both grammatical aspect and time reference) per each mediator. The first set of path models examines the direct effects of age and education, as well as the mediating effects of verbal WM, inhibition, perceptual SOP, and motor SOP on VRMP (Fig. 3). The second set of path models tests the direct effect of verbal WM on VRMP, and the mediating effects of inhibition, perceptual SOP, and motor SOP on VRMP (Fig. 4).

The model summary of all path models described below had an excellent fit of the model (Kline, 2011) with Root Mean Square Error of Approximation less than 0.08, Comparative Fit Index higher than 0.90, Tucker−Lewis Index higher than 0.90, and Standardized Root Mean Square Residual less than 0.8 (see Supplementary Materials—Tables S2−S8 for the full model output).

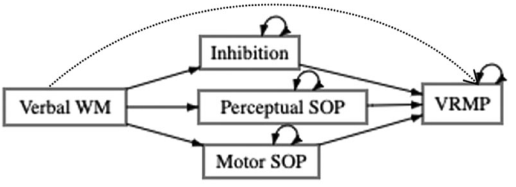

Fig. 4. The path diagram illustrates the direct effect of verbal working memory (WM) on verb-related morphosyntactic production (VRMP) (dotted line), as well as the mediating effects of inhibition, perceptual speed of processing (SOP), and motor SOP on VRMP (solid lines).

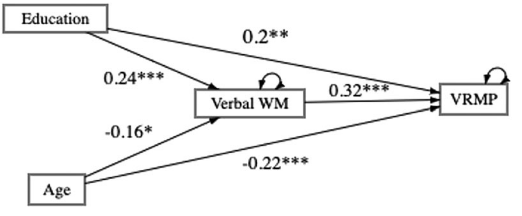

Fig. 5. The path diagram depicts the direct and indirect relationship between education/age and verbal working memory (WM) on verb-related morphosyntactic production (VRMP). The symbol * indicates significant effects.

The first set of path models revealed that the relationships between age and VRMP, and between education and VRMP were partially mediated by verbal WM (Fig. 5). Verbal WM in this case is a *partial* mediator—since even after accounting for the mediating effect of verbal WM on VRMP (for age model: $E = -.004$, $p = .04$; for education model: $E = 0.07$, $p = .004$), there still remains a significant direct effect of age on VRMP ($E = -.27$, $p < .001$), as well as of education on VRMP ($E = .27$, $p < .001$). Inhibition, perceptual SOP, and motor SOP did not mediate the relationship between age and VRMP, nor that between education and VRMP (see Supplementary Materials—Tables S2−S5 for the full model output).

The second set of path models revealed that the relationship between verbal WM and VRMP was partially mediated by perceptual SOP (Fig. 6). That is, there was a significant direct effect of verbal WM on VRMP ($E = .42$, $p < .001$) and a significant indirect effect of verbal WM on VRMP via perceptual SOP ($E = .07$, $p = .004$). No significant mediation effects were found for inhibition or motor SOP (see Supplementary Materials—Tables S6−S8 for the full model output).

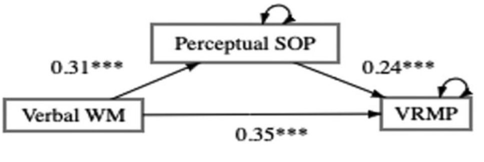

Fig. 6. The path diagram depicts the direct and indirect relationship between verbal working memory (WM) and perceptual speed of processing (SOP) on verb-related morphosyntactic production (VRMP). The symbol * indicates significant effects.

5. Discussion

In this study, we investigated the role of locality, age, education, sex, verbal STM, verbal WM, motor SOP, perceptual SOP, inhibition, and morphosyntactic category (grammatical Aspect and Time Reference/Tense) in VRMP.

The first research question was whether locality interacts with any of the memory systems examined here, namely, verbal WM, verbal STM, and LTWM for language, as reflected in years of formal education. We expected to replicate Fyndanis et al.'s (2022) finding; that is, we predicted a significant interaction between locality and LTWM for language. However, locality did not interact with any of the three memory systems considered here. This was the case both when analyzing the full data set (based on 200 participants) and when analyzing the data set of those participants who were aged between 45 and 80 years ($N = 84$). The latter analysis was performed to ensure comparability between the current study's results and Fyndanis et al.'s (2022) results, which were based on middle-aged and older neurotypical participants. In fact, in Fyndanis et al. (2022), the significant interaction between locality and LTWM for language (as reflected in years of formal education) emerged not only in a sample of 80 participants aged between 55 and 67 years, but also in an expanded data set of 140 neurotypical participants aged between 45 and 86 years. The discrepancy between the present study and Fyndanis et al.'s (2022) study regarding the above interaction could be partly explained in terms of variance in years of formal education, as Fyndanis et al.'s (2022) participants presented more variance in this demographic variable (*Mean Education* [years] [SD] = 13.1 [4.5]; *Education Range* [years] = 6−22) compared to the present study's participants (entire group of participants [$N = 200$]: *Mean Education* [years] [SD] = 15 [3]; *Education Range* [years] = 6−24; subgroup of 84 middle-aged and older participants: *Mean Education* [years] [SD] = 14.1 [3.5], *Education Range* [years] = 6−24). The discrepancy between the studies regarding the above interaction could also be attributed to the superior performance of the present study's participants in the VRMP task compared to that of Fyndanis et al.'s (2022) participants (Current study, full data set [$N = 200$]: Time Reference Mean accuracy [SD] = 98.4% [4.8%]; Aspect Mean accuracy [SD] = 89.6% [13.5%]; current study, data set of middle-aged and older participants [$N = 84$]: Time Reference Mean accuracy [SD]: 97.4% [6.1%]; Aspect Mean accuracy [SD]: 85.4% [16.1%]; Fyndanis et al. [2022]: Time Reference Mean accuracy [SD] = 95.2% [10.4%], Aspect Mean accuracy [SD] = 76.5% [20.4%]). The difference between the two studies in participants' performance level on VRMP means that, in the current study, there was less room for a significant interaction between locality and education to be detected. It might also be that the present study does not have sufficient power to detect such an interaction. Future studies testing significantly larger groups of middle-aged and older neurotypical participants should seek to replicate Fyndanis et al.'s (2022) finding. Focusing on middle-aged and older participants when seeking to replicate Fyndanis et al.'s (2022) finding is crucial, as such participants display more variation in accuracy performance on VRMP as well as in verbal STM/WM capacity and in efficiency of LTWM for language, compared to younger participants.

We also investigated which demographic, cognitive, and task/material-related factors play a role in VRMP (Research Question 2a). Three related questions were whether VRMP is supported by both the storage and processing components of verbal WM (Research Question 2b), whether VRMP is supported by both verbal WM and LTWM for language (Research Question 2c), and whether grammatical aspect and time reference dissociate (Research Question 2d). We predicted (based on Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022) that significant main effects of verbal WM, verbal STM, education/LTWM for language, and age would emerge. We also expected to find significant main effects of inhibition and SOP, because both cognitive capacities have been found to affect WM functioning (e.g., Fry & Hale, 1996, 2000; Hasher & Zacks, 1988; Salthouse, 1992). Furthermore, inhibition should be critically involved in transformational sentence completion tasks (see background information about inhibition in Section 1.1), and SOP was found to moderately correlate with participants' accuracy performance on the production of grammatical aspect and time reference in Fyndanis et al. (2022). Lastly, given the dissociation between grammatical aspect and time reference that was consistently reported by Fyndanis and colleagues for different populations (for neurotypical adults in Fyndanis, Arcara et al., 2018; Fyndanis et al., 2022; for individuals with agrammatic aphasia in Fyndanis et al., 2012; Fyndanis, Arcara et al., 2018; for individuals with DAT in Fyndanis et al., 2013; and for individuals with multiple sclerosis in Fyndanis et al., 2020), we predicted that the participants would make significantly more aspect errors than time reference errors.

We found significant main effects of age (participants' performance on VRMP dropped with age), verbal WM capacity (the greater the participants' verbal WM capacity, the better their performance on VRMP), education (the higher the educational level, the better the accuracy performance on VRMP), motor SOP (the slower the motor SOP, the better the accuracy performance on VRMP), locality (significantly more errors occurred in nonlocal than in local configurations), and morphosyntactic category (with participants performing worse on grammatical aspect than on time reference).

The significant main effect of verbal WM capacity on VRMP replicates Fyndanis, Arcara et al.'s (2018) and Fyndanis et al.'s (2022) findings about the important role of verbal WM in VRMP. Moreover, the path analysis revealed that VRMP is affected by verbal WM both directly and indirectly. Specifically, it was found that the relationship between verbal WM and VRMP is partially mediated by perceptual SOP. This is not surprising, as SOP is closely related to WM (Fry & Hale, 1996, 2000) and individual differences in WM largely reflect individual differences in SOP (Salthouse, 1992). This result is also consistent with the fact that perceptual SOP was significantly and positively correlated with both verbal WM capacity and accuracy performance on the production of both grammatical aspect and time reference.

The absence of an effect of verbal STM capacity on VRMP, coupled with the significant main effect of verbal WM capacity, suggests that it is predominantly the processing component of WM (and not its storage component) that subserves VRMP. This finding is in line with Fyndanis, Arcara et al. (2018) but at odds with Fyndanis et al. (2022). The discrepancy might be related to the fact that, while we measured verbal STM using a single task, verbal WM was tested with two tasks, based on which composite scores for verbal WM capacity were computed. Composite scores provide more reliable estimates of the cognitive construct being measured compared to scores from single tasks (Waters & Caplan, 2003). An alternative interpretation of these results is that not only the digit ordering span task and digit backward span task, but also the digit forward span task taps verbal WM, with the former two being more reliable measures of WM. This possibility is consistent with Kane, Conway, Hambrick, and Engle's (2008) view that span tasks "cannot be dichotomized as reflecting either STM or WMC [Working Memory Capacity], or either storage or executive control, because all immediate memory tasks are complex and determined by a host of factors, including both storage and executive attention" (p. 38). This view emphasizes the role of executive attention in measures of STM/WM capacity, as it posits that variation in STM/WM capacity reflects individual differences in executive attention (Kane et al., 2008).

The significant main effect of age on VRMP replicates Fyndanis, Arcara et al.'s (2018) result about the role of age in VRMP. Furthermore, the path analysis showed both direct and indirect effects of age on VRMP. Specifically, it was found that the relationship between age and VRMP was partially mediated by verbal WM, rather than by inhibition, motor SOP, or perceptual SOP. The fact that the path analysis provided evidence not only for an indirect effect but also for a direct effect of age on VRMP does not necessarily mean that age affects VRMP in a direct way. It might be that age directly affects additional cognitive capacities not tested here, such as monitoring and attention, which in turn affect VRMP (e.g., Naveh-Benjamin & Cowan, 2023). Moreover, there might be an age-related weakening of the connections in long-term memory between the nodes of aspectual adverbials and verb forms marking perfective versus imperfective aspect, as well as between the nodes of temporal adverbials and verb forms marking past versus future reference. VRMP could also be affected by time-related characteristics of the environment, which differentially affect different cohorts of participants (a.k.a. cohort effects; see Salthouse, 2013, and references therein). Note that only indirectly is age related to cohort effects. The idea that age only indirectly affects VRMP is consistent with Salthouse's (2013) view that age is not a causal factor and that causal variables could be identified and replace the age factor in accounts of what are currently conceptualized as relationships between age and various cognitive functions (including aspects of language production). A clinical implication of the aforementioned results is that treatment protocols for adults with impaired VRMP should not only target VRMP directly but also address cognitive capacities directly influenced by age and directly impacting VRMP. The present findings suggest that one such cognitive capacity is verbal WM.

The significant main effect of education replicates Fyndanis et al.'s (2022) finding highlighting the role of education in VRMP. Although the path analysis showed both direct and indirect effects of education on VRMP (with verbal WM partially mediating the relationship between education and VRMP) (Fig. 5), just like age, education might not have a direct effect on VRMP; that is, it might not be a causal factor. The partially direct effect of Education on VRMP, which is depicted in the path diagram in Fig. 5, could be replaced by causal factors such as perceptual SOP, verbal STM, and inhibition (as there were significant weak-to-moderate correlations between education and these cognitive constructs), as well as (the efficiency of) a procedural memory system supporting language production. In other words, we interpret the partially direct effect of education on VRMP as indicative of perceptual SOP, verbal STM, inhibition, and a procedural memory system, potentially LTWM for language (Caplan & Waters, 2013), which, alongside the above cognitive abilities, also supports

VRMP. This interpretation rests on the assumption that education is a proxy for the quality and quantity of an individual's "language skill" which determines the efficiency of LTWM for language (for more details, see Section 1.1.3). Education is commonly used as a proxy for other constructs as well, such as cognitive reserve (e.g., Arenaza-Urquijo, Wirth, & Chételat, 2015, and references therein) and socioeconomic status (Entwisle & Astone, 1994). Linking education to cognitive constructs such as LTWM for language, however, offers a more specific (i.e., less vague) account of the involvement of education in VRMP. The present findings, therefore, replicate Fyndanis et al.'s (2022) finding that VRMP is supported by both verbal WM and LTWM for language.

The significant main effect of locality is in line with Fyndanis et al. (2022), but at odds with Fyndanis, Arcara et al. (2018). One might deduce that nonlocal configurations tax the processing system, increasing the probability of erroneous VRMP. However, none of the three memory systems considered here, that is, verbal STM, verbal WM, and LTWM for language, interacted with locality, suggesting that local and nonlocal configurations do not pose differential demands on any of the above memory systems. This does not agree with Fyndanis et al.'s (2022) finding that LTWM for language interacted with locality affecting VRMP more in local than in nonlocal configurations.

The detrimental effect of motor SOP on accuracy performance in VRMP appears unexpected at first glance. However, previous findings on the relationship between motor SOP and cognitive performance might shed light on this result. Salthouse (1996) found that motor SOP is positively related to decision/response time but not to accuracy performance in cognitive tasks tapping memory, reasoning, and spatial ability. Moreover, he found that accuracy performance in cognitive tasks was positively related to perceptual SOP. Given these findings, the negative effect of motor SOP on accuracy performance on VRMP could be accounted for by assuming that motor SOP positively affects decision/response time in the sentence completion task tapping VRMP, and that there is a trade-off between response time and accuracy; hence, the negative impact of motor SOP on accuracy performance on VRMP. As shown in the correlation matrix (Table 3) and in the path diagram in Fig. 6, it is only the perceptual component of SOP that positively affects accuracy performance on VRMP, which is consistent with Salthouse's (1996) results and conclusion that perceptual SOP "affects the quality of cognitive processing" (p. 418).

Results from the regression analyses did not bear out our prediction for a role of inhibition in VRMP. Moreover, the path analyses did not reveal a mediating effect of inhibition in the relationship between verbal WM capacity and VRMP. A possible explanation is that the influence of this cognitive capacity on VRMP is not as robust as that of the other cognitive functions tested; thus, its role may be overshadowed in our data set. Related to this, inhibition was significantly correlated with verbal WM, motor SOP, and education/LTWM for language (Table 3), which all yielded significant main effects. A limitation that we acknowledge is that we used only one task that tapped into inhibition. In future research, we plan to use more robust methods to measure it; for example, we could use the Flanker Squared, Simon Squared, and Stroop Squared tasks (Burgoyne, Tsukahara, Mashburn, Pak, & Engle, 2023) and extract the latent variable, which should reflect a more accurate measure of inhibition. Future studies using more robust methods to measure inhibition and testing larger cohorts of participants might be able to detect an inhibition effect.

We also addressed whether any of the variables yielding significant main effects interact with the production of time reference and grammatical aspect (Research Question 3). Based on Fyndanis et al. (2022), we expected locality to affect grammatical aspect but not time reference. This prediction was not borne out, as there was no significant interaction between Morphosyntactic Condition and locality. Furthermore, there was no significant interaction between Morphosyntactic Condition and verbal WM, which is consistent with Fyndanis et al. (2022), who found that verbal WM comparably affected grammatical aspect and time reference, but contra Fyndanis, Arcara et al. (2018), who found that verbal WM affected aspect more than time reference. Thus, it remains unclear whether verbal WM differentially affects grammatical aspect and time reference, shaping the identical pattern of performance (i.e., aspect < time reference) observed in various Greek-speaking populations (as discussed earlier). Future studies with larger samples of participants—ideally consisting of middle-aged and older individuals—could reveal whether verbal WM affects grammatical aspect more than time reference, and whether locality differentially affects the production of grammatical aspect and time reference. Moreover, based on Fyndanis et al. (2022), we expected no interaction to emerge between education/LTWM for language and Morphosyntactic Condition. Results replicated this finding. Lastly, there was no significant interaction between age and Morphosyntactic Condition, meaning that age comparably affected time reference and aspect. To the best of our knowledge, no other study addressed whether age differentially affects the production of time reference and grammatical aspect. It appears that both morphosyntactic categories are equally demanding in terms of processing resources. Therefore, age-related decline in cognitive capacities that support VRMP similarly affects the production of time reference and aspect. This is consistent with the fact that neither verbal WM nor motor SOP interacted with production of time reference and aspect. This suggests that the dissociation between time reference and grammatical aspect is not shaped by any of these variables. This dissociation, observed when testing VRMP by means of transformational sentence completion tasks, could be accounted for by assuming that, in the mental lexicon, the connections between the nodes of aspectual adverbials and the nodes of verb forms or morphemes marking grammatical aspect are weaker than the connections between temporal adverbials and verb forms or morphemes marking tense. This might be because, at least in Greek, temporal adverbials are more frequent than aspectual adverbials.

The final research question (Research Question 4) was about the role of sex in VRMP. Motivated by several previous findings showing a female advantage in various aspects of language production (e.g., Angelopoulou et al., 2020; Ardila & Rosselli, 1996; Moscoso del Prado Martín, 2017; Weiss et al., 2003), we asked whether there is a female advantage in VRMP, and whether the relationship between age and VRMP is modulated by sex. There was no significant main effect of sex on VRMP. Moreover, the results showed that the relationship between age and accuracy performance on VRMP is not modulated by sex. To the best of our knowledge, no other study has addressed whether accuracy performance on tasks tapping production of time reference and/or grammatical aspect is modulated by participants' sex. Likewise, no other study has investigated whether sex interacts with age when it comes to production of time reference and/or grammatical aspect tested with sentence completion tasks. Significant sex effects on language production have primarily been observed in lexical abilities, as evidenced by performance on verbal fluency tasks (e.g., Weiss et al., 2003) and picture naming tasks (e.g., Simos et al., 2011), as well as in discourse production, particularly concerning verb frequency (Angelopoulou et al., 2020). Notably, significant interactions between sex and age have been predominantly identified in discourse production measures, such as the diversity of syntactic structures (Moscoso del Prado Martín, 2017) and the amount of spontaneous speech (Ardila & Rosselli, 1996). While most studies have reported a female advantage (e.g., Angelopoulou et al., 2020; Ardila & Rosselli, 1996; Moscoso del Prado Martín, 2017; Weiss et al., 2003), our findings suggest that this advantage is not observed across-the-board. In contrast, our results indicate that sex affects age-related decline of VRMP in aging neurotypical individuals in a comparable manner.

5.1. Study limitations and future directions

A limitation of the study was the use of single measures for the assessment of verbal STM, perceptual SOP, motor SOP, and inhibition. Composite scores based on two or more tasks provide better estimates of the capacity of the cognitive constructs being assessed compared to single measures' scores (e.g., Salthouse, 2013; Waters & Caplan, 2003). As mentioned above, an alternative way to reliably estimate the capacity of each cognitive construct is to use three tasks tapping the same construct and then extract the latent variable (Burgoyne et al., 2023).

Moreover, the study did not consider some cognitive constructs that may affect VRMP, such as attention and monitoring. Therefore, future research should examine the role of more cognitive capacities in VRMP than the present study did, and at least two measures of each cognitive capacity should be used.

Another limitation of the study is related to its cross-sectional nature. Cross-sectional studies on the role of aging in cognitive functioning (which, broadly construed, also encompasses VRMP) could be "considered misleading, because assessments at different ages are based on different people who could vary in characteristics other than age that might affect their levels of cognitive functioning" (Salthouse, 2016, p. 932). In contrast, longitudinal studies are more informative about the relationship between age and cognitive functioning than are cross-sectional studies, as they involve longitudinal within-subject comparisons, that is, comparisons between the same participants' performances on cognitive (or linguistic) tasks at different ages (Salthouse, 2016). Therefore, longitudinal studies should seek to replicate the present results.

6. Conclusions

In sum, the current study investigated the role of locality (a material-related variable), demographic factors (age, [years of formal] education, and sex), cognitive capacities (verbal WM, verbal STM, motor SOP, perceptual SOP, and inhibition), and morphosyntactic category (time reference and grammatical aspect) in VRMP. A battery of seven tasks was administered to 200 neurotypical Greek-speaking participants, aged between 19 and 80 years. Generalized linear mixed-effects models revealed significant main effects of locality, age, education, verbal WM capacity, motor SOP, and morphosyntactic category. More morphosyntactic errors occurred in nonlocal than in local configurations; the older the participants and the lower their education level, the worse their performance in the task tapping VRMP; the greater the participants' verbal WM capacity, the better their performance in the VRMP task; the higher their motor SOP, the worse their accuracy performance in the VRMP task; participants fared significantly better on time reference than on grammatical aspect. Production of time reference and grammatical aspect did not interact with any of the above significant factors. Moreover, locality did not interact with any memory system. Path analyses revealed that the relationships between age and VRMP, and between education and VRMP were partially mediated by verbal WM; and the relationship between verbal WM and VRMP was partially mediated by perceptual SOP. Results suggest that subject-, task/material-, and morphosyntactic category-specific factors determine accuracy performance on VRMP; and the effects of age, education, and verbal WM on VRMP appear to be partly indirect. Nevertheless, we argue that the effects of age and education on VRMP may be fully indirect. The fact that there was a significant main effect of verbal WM but not of verbal STM on accuracy performance in the VRMP task suggests that it is predominantly the processing component (and not the storage component) of verbal WM that supports VRMP. Lastly, we interpret the results as suggesting that VRMP is also supported by a procedural memory system whose efficiency might be reflected in years of formal education.

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Notes

1 It should also be noted that half of the time reference items elicited past reference, and half future reference; and half of the grammatical aspect items elicited perfective aspect, and half imperfective aspect. Overall, there were 24 local past reference items, 24 local

future reference items, 24 nonlocal past reference items, 24 nonlocal future reference items, 24 local perfective aspect items, 24 local imperfective aspect items, 24 nonlocal perfective aspect items, and 24 nonlocal imperfective aspect items.

2 Before finalizing the task, we administered it to five young neurotypical adults to make sure that all experimental items elicited the expected (*target*) verb forms. Indeed, this was the case.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab of this article:
Supporting Information

Appendix

Verbs included in the sentence completion task.

Greek verb	Greek verb (transliteration)	English translation
πλέκω	*pléko*	knit
ντύνω	*díno*	dress
στρώνω	*stróno*	smooth/flatten
λούζω	*lúzo*	shampoo/wash/bathe
λύνω	*líno*	solve
στήνω	*stíno*	set up
σβήνω	*svíno*	turn off
χτίζω	*χtízo*	build
ψήνω	*psíno*	roast/bake
ράβω	*rávo*	sew
σκάβω	*skávo*	dig
κόβω	*kóvo*	cut